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13. ABSTRACT *(Maximum 200 words)* Enhanced biological reductive dechlorination (EBRD) shows a great deal of promise for efficiently treating groundwater contaminated with chlorinated solvents, but demonstration sites around the country were reporting mixed results. Because individual demonstrations commonly used dissimilar methods, the limitations of the technology were not clear and its applicability at any given site was unknown. As a result, the Environmental Security Technology Certification Program (ESTCP) invested in the development of a standardized protocol to test the technology's effectiveness at any site. A draft protocol was developed that included microcosm and field-testing and an extensive array of sampling and monitoring. Once developed, the draft protocol was applied at four sites to evaluate its overall effectiveness. Data generated at the four sites was used to refine the protocol by eliminating less valuable components while maintaining a testing methodology that provides scientifically defensible data that would satisfy the regulatory community at a reasonable cost. Microcosm testing was used to evaluate the performance of a suite of electron donors, which included yeast extract, lactate, butyrate, benzoic acid, propionic acid, and acetic acid. The testing examined the rate, onset, and extent of dechlorination as well as donor fermentation pathways. Microcosm testing data revealed an apparently heterogeneous distribution of dechlorinating organisms within individual sites, and that most electron donors will eventually yield the same dechlorination endpoint, though the onset and rate of dechlorination may differ significantly. The electron donor showing the most rapid and complete dechlorination in microcosm studies (usually butyrate) was used in the four 6-month field demonstrations. Reductive dechlorination was stimulated at all four field sites. At three of the four sites complete dechlorination of PCE and TCE to ethene was achieved. At the fourth site, which was initially aerobic, dechlorination appeared to stop at vinyl chloride, despite the fact that microcosm results demonstrated complete dechlorination to ethene. At each of the field sites the onset of dechlorination occurred within 5 weeks of electron donor injection and the subsequent dechlorination of parent chloroethenes was very rapid. Field systems were robust and were not susceptible to upset by interruptions in electron donor supply or TCE concentrations that reached 169,000 ppb.

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The objective of this effort is to develop and demonstrate a treatability testing procedure for enhanced in situ anaerobic dechlorination of chlorinated solvents in groundwater. This project consisted of three specific objectives. First, to develop a draft technical protocol that describes in detail how to conduct a treatability test for enhanced anaerobic dechlorination. Second, apply the draft protocol at four sites contaminated with chlorinated ethenes. Third, finalize the draft protocol based on the site-specific test results. The results will facilitate the rapid transition of this technology from the field research arena to being a n accepted remediation technology for contaminated sites.

KEY WORDS:RABBIT, Anaerobic, Biodegredation, Trichloroethene, In Situ, Bioremediation

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Cost and Performance Report for

REDUCTIVE ANAEROBIC BIOLOGICAL IN SITU TREATMENT TECHNOLOGY (RABITT) TREATABILITY TESTING

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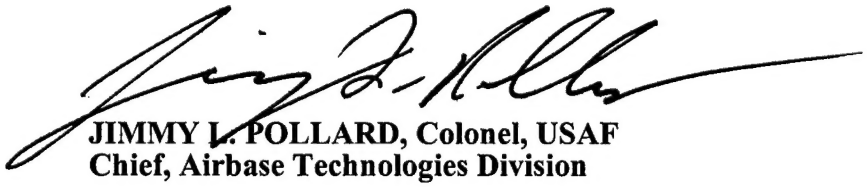

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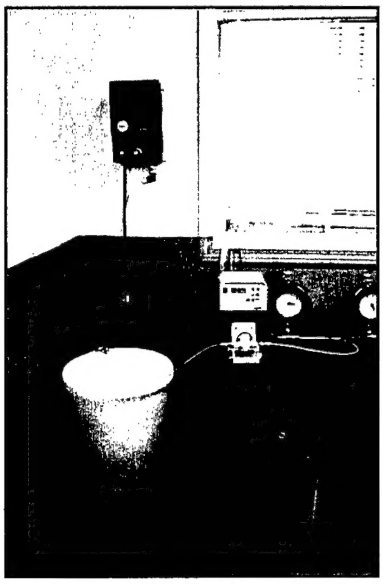
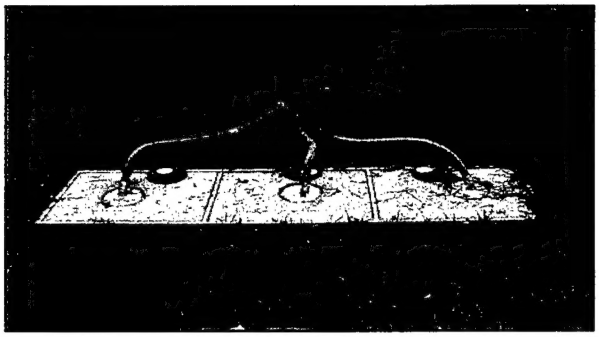
Cost and Performance Report

for

Reductive Anaerobic Biological In Situ Treatment Technology (RABITT) Treatability Testing





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Abbreviations and Acronyms

bgs	below ground surface
CFR	Code of Federal Regulations
DCE	dichloroethene
DERP	Defense Environmental Restoration Program
DOC	dissolved organic carbon
DoD	(U.S.) Department of Defense
EBRD	enhanced biological reductive dechlorination
FRTR	Federal Remediation Technologies Roundtable
HAZWOPER	hazardous waste operations
IRP	Installation Restoration Program
ITRC	Interstate "Technologies Regulatory Council
IW	injection well
MNA	monitored natural attenuation
MP	monitoring probe
MW	monitoring well
NAPL	nonaqueous-phase liquid
O&M	operations and maintenance
OSHA	Occupational Safety and Health Administration
PCE	perchloroethene
ppb	parts per billion
PVC	polyvinyl chloride
RABITT	reductive anaerobic biological in situ treatment technology
TCE	trichloroethene
U.S. EPA	United States Environmental Protection Agency
UIC	underground injection control
VC	vinyl chloride
VOC	volatile organic compound

1. Executive Summary

Background

The chemical properties of the chlorinated solvents perchloroethene (PCE) and trichloroethene (TCE) make them particularly difficult groundwater contaminants to remediate, but laboratory research and field observations have shown that PCE and TCE may be reductively dechlorinated to ethene by microorganisms indigenous to contaminated environments (DiStefano et al. 1991; Major et al. 1991). These findings led to the rapid development of a variety of enhanced biological reductive dechlorination (EBRD) technologies that seek to exploit the remedial capabilities of these microorganisms.

Although EBRD shows great potential to effectively treat chlorinated solvent plumes, it is seldom employed because those responsible for implementing site cleanups do not always have a complete understanding of the reductive dechlorination process. Even at sites with laboratory and/or field data that strongly suggest a positive outcome using EBRD technologies, the best method to apply this type of in situ approach has not been clear.

Despite concerns regarding its application, EBRD still promises to be a very cost-effective tool for remediating sites contaminated with chloroethenes. It was envisioned that a standardized protocol might serve to alleviate concerns and foster its use at favorable sites while preventing its implementation at inappropriate sites. This led to the development of a draft technical protocol entitled, *A Treatability Test for Evaluating the Potential Applicability of the Reductive Anaerobic Biological In Situ Treatment Technology (RABITT) to Remediate Chloroethenes* (Battelle, 1997). This document, which would become more commonly known as the RABITT protocol, presents detailed instructions for assessing the applicability of in situ enhanced biological reductive dechlorination at a specific site.

Objectives of the Demonstration

The RABITT project consisted of three specific objectives. The first objective was to develop a draft technical protocol that describes in detail how to conduct a treatability test for enhanced anaerobic dechlorination. The second objective was to apply the draft protocol at four selected demonstration sites contaminated with chlorinated ethenes. The third objective was to evaluate the performance of the draft protocol at each of the four sites and to finalize it based on the site-specific test results. The objective of individual demonstrations was to use the draft RABITT treatability test protocol to evaluate whether appropriate microbial populations and geochemical conditions existed or could be produced in situ to support the biological reduction of chloroethenes to ethene.

Regulatory Drivers

A 1997 report estimated that Department of Defense (DoD) owned more than 3,000 sites in the United States contaminated with chlorinated hydrocarbons, and that TCE is one of the two most common contaminants (United States Environmental Protection Agency [U.S. EPA], 1997). Although many sites are becoming dated, new spills continually add to the problem. Almost 500

new chlorinated hydrocarbon spills at DoD sites were reported to the U.S. EPA between 1987 and 2000 (U.S. EPA, 2001). The DoD goals for Installation Remediation Program (IRP) sites like these is to have all of the 27,000 IRP locations (high-, medium-, and low-risk) cleaned up, or in the process of being cleaned up, by 2014 (DERP, 2001). Technologies that target recalcitrant contaminants, such as TCE, can assist in meeting these cleanup goals.

Demonstration Results

Results from the field demonstrations showed relatively short lag periods, rapid parent compound degradation, and, with the exception one site, substantial conversion of parent compounds to ethene. Reductive dechlorination began only 3-5 weeks after starting electron donor injection, and parent compounds were quickly degraded, with half-lives measured in hours. In addition, large portions of the parent compounds were converted to ethene at three of the four demonstration sites.

Microcosm testing showed that selection of the electron donor typically did not change the most reduced daughter product detected, but it did influence the rate and therefore the extent of dechlorination. Although the endpoint of the dechlorination reaction typically was not affected by the choice of electron donor, the time until the onset of dechlorination and the rate of dechlorination were both affected. Donors with shorter lags and/or faster dechlorination rates achieved higher molar conversions after six months. Overall, butyrate provided the most complete dechlorination within six months and was therefore selected for use at three of the four field sites, but lactate usually did not lag far behind.

Stakholder/End-User Issues

The RABITT treatability test system consists of simple components that can be operated easily by a properly trained technician. The treatability test exclusively uses commercial off-the-shelf components that can be tailored to accommodate site-specific conditions. Interpreting data to make system adjustments during the initial operational period requires an individual familiar with subsurface ecology, hydrology, and geochemistry; however, once the system begins to approach steady-state operation, the need for system adjustments diminishes. The simplified nature of the field treatability test described in the revised RABITT protocol requires relatively little expertise in the area of bioremediation to analyze the test results. Data analysis is based on determining the endpoint for the dechlorination process and the relative proportion of parent compound converted to ethene (or other desired endpoint).

2. Technology Description

2.1 Technology Development and Application

The chemical properties of the chlorinated solvents PCE and TCE make them particularly difficult groundwater contaminants to remediate. Both are relatively insoluble and hydrophobic; consequently, these compounds tend to form ganglia of nonaqueous-phase liquid (NAPL) and sorb to subsurface organic material. Their oxidized nature makes them resistant to aerobic biodegradation. Conventional pump-and-treat systems are ineffective because they are limited by the slow dissolution of these contaminants into the aqueous phase. The difficulty in pumping PCE and TCE to the surface for treatment has resulted in a search for an effective in situ treatment alternative. One promising alternative is enhanced in situ biologically catalyzed reductive dechlorination.

Laboratory research and field observations have shown that PCE and TCE may be reductively dechlorinated to ethene by microorganisms that are indigenous to contaminated environments (DiStefano et al. 1991; Major et al. 1991). These findings led to the rapid development of a variety of cleanup technologies that seek to exploit the remedial capabilities of these microorganisms. Although each of these technologies has distinguishing features, they all attempt to stimulate the dechlorination of chloroethenes by supplying electron-donating substrate to indigenous anaerobic microorganisms. There may be differences in the selected electron donor or how it is applied, but the underlying process is fundamentally the same.

Although EBRD shows great potential to effectively treat chlorinated solvent plumes, it is seldom employed. The parties responsible for implementing site cleanups often do not have a complete understanding of the reductive dechlorination process, and those who do are frequently left with uncertainty regarding the outcome of such a remedial strategy. Even at sites with laboratory and/or field data that strongly suggest a positive outcome, the best method to apply this type of in situ approach has not been clear.

Despite concerns regarding its application, EBRD still promises to be a very cost-effective tool for remediating sites contaminated with chloroethenes. It was envisioned that a standardized protocol might serve to alleviate concerns and foster its use at favorable sites while preventing its implementation at inappropriate sites. This led to the development of a draft technical protocol entitled, *A Treatability Test for Evaluating the Potential Applicability of the Reductive Anaerobic Biological In Situ Treatment Technology (RABITT) to Remediate Chloroethenes* (Battelle, 1997). This document, which would become more commonly known as the RABITT protocol, presents detailed instructions for assessing the applicability of in situ enhanced biological reductive dechlorination at a specific site.

2.2 Process Description

The RABITT treatability test described in the RABITT protocol is a multiple-step process for examining the potential for achieving enhanced in situ biological reductive dechlorination at a site. The protocol describes laboratory microcosm and field test methods designed to evaluate

the response of indigenous microorganisms to the addition of soluble electron donating substrates. Increased rates of degradation and/or a furthering in the extent of parent compound dechlorination demonstrate the enhancement of the reductive dechlorination process.

The reductive dechlorination of PCE to ethene proceeds through the series of hydrogenolysis reactions shown in Figure 2-1, with each one becoming progressively more difficult to carry out. For this reason DCEs, particularly *cis*-dichloroethene (*cis*-DCE), and vinyl chloride (VC) sometimes accumulate in anaerobic environments. Therefore, both the rate of dechlorination and the extent of dechlorination is important in evaluating the effectiveness of the various electron donors used for treatability testing. A more detailed discussion about microbially catalyzed reductive dechlorination can be found in Section 2.2 of the draft RABBIT protocol (Battelle, 1997).

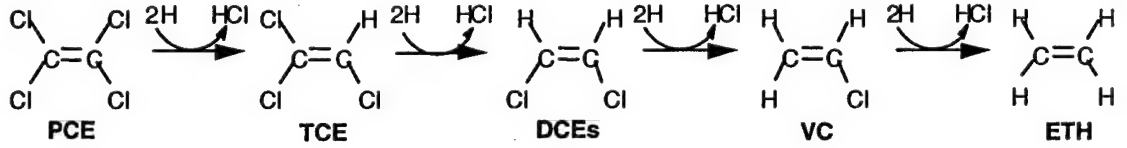

Figure 2-1. Reductive Dechlorination of PCE

2.2.1 Testing and Monitoring Rationale. The testing process described in the draft protocol included a preliminary site assessment, testing preparations, microcosm testing, field testing, and data analysis. The draft protocol was developed based on the monitoring of all aspects of reductive dechlorination and, as such, is more expansive than necessary to evaluate the potential for in situ process enhancement. The intent was to evaluate the comprehensive data set and screen it down to methods/procedures that provided value for evaluating the potential for successful reductive dechlorination enhancement. For example, both laboratory microcosm and field testing were included in the draft protocol, even though it was understood that including both would result in a very expensive test. The objectives of including both were to evaluate the strengths and weaknesses of each test, as well as to make a comparison between the two approaches at the four sites and determine what value each test provided. The goal was to determine if one test was superior in all cases, or if elements of both were needed to assess the potential for successful enhancement of the reductive dechlorination process. The results from implementation of the draft protocol at four sites then were used to determine the methods to include in the final protocol (Battelle, 2002a).

Similarly, the draft protocol was written with a heavy dose of monitoring requirements that included the collection of groundwater samples every two weeks. At the time the protocol was drafted, it was assumed that this level of monitoring would not be required in the final version,

but it was necessary in the draft version to ensure that sufficient data were collected. Although this approach allowed a more thorough testing of the protocol itself, it did serve to considerably raise the costs of conducting the test described in the draft protocol.

2.2.2 Protocol Implementation. The draft protocol was applied at four DoD sites with different hydrogeologic characteristics and contaminant profiles. The four sites included Facility 1381 at Cape Canaveral Air Station, FL; Site 4 at Alameda Point, CA; the East Gate Disposal Yard at Fort Lewis, WA; and Site 88 at Marine Corps Base Camp Lejeune, NC. Details on site selection, preliminary site assessment, testing preparations, microcosm testing, field testing, and data analysis can be found in the draft protocol (Battelle, 1997) and in Section 3.0 of this report. The expansive nature of the draft protocol and its implementation at four sites resulted in the generation of a tremendous amount of data that were used to refine the draft protocol into a final version (Battelle, 2002a). The final version will serve as a guide for implementation at DoD sites that have chlorinated solvent contamination and which for one or more reasons cannot achieve cleanup using monitored natural attenuation (MNA).

2.2.3 Training/Health and Safety Considerations. Specific training and health and safety precautions are based on the type of activities to be performed for field treatability and microcosm testing. Personnel responsible for sampling will be trained in the proper methods of sample collection, handling, and transportation. In addition, all field personnel working in the investigation area will have completed the Occupational Safety and Health Administration (OSHA)-required 40-hour hazardous waste operations (HAZWOPER) training course as mandated by 29 Code of Federal Regulations (CFR) 1910.120, as well as required 8-hour refresher courses as appropriate. Field activities typically require Level D personal protective equipment at the site, but site-specific factors will ultimately determine the appropriate level of protection.

2.2.4 Ease of Operation. The RABITT treatability test system consists of simple components that can be operated easily by a properly trained technician, but interpreting data to make system adjustments during the initial operation period will require an individual familiar with subsurface ecology, hydrology, and geochemistry. The first two weeks of system operation will require considerable attention as groundwater injection and extraction rates, and electron donor feed rates are evaluated. Once the system begins to approach steady-state operation, the need for system adjustments will diminish, but sample collection will still be required on a regular basis (approximately once a month based on protocol revisions).

The RABITT treatability test exclusively uses commercial off-the-shelf components, but it must be tailored to accommodate site-specific conditions. Examples of customization include well specifications (e.g., well depths) and the selection of an appropriate tracer. Because RABITT treatability test components are commercially available, environmental contractors should find the technology easy to implement.

2.3 Previous Testing of the Technology

The EBRD process has been extensively researched over the past two decades, but the implementation of the process as a technology for site remediation is only in the developmental stages. More pilot-scale tests/demonstrations have been conducted where the dechlorination efficiency has been the focus of the efforts, with scale-up to full-scale implementations lagging. This is in part due to the attention given to MNA, a technology that earlier was thought to be more widely applied than is proving to be true. Once the realization was made that MNA was not applicable at all chlorinated solvent sites, the attention was refocused back onto engineered approaches.

2.4 Advantages and Limitations

The main strength of the RABITT protocol is that it provides an inexpensive method for screening sites for application of EBRD. Unlike petroleum hydrocarbon degradation, reductive dechlorination is not guaranteed at all sites because of more "specialized" microbial and geochemical requirements. Application of the RABITT protocol precedes the more extensive and expensive procedures required for applying EBRD at full-scale. The goal is to prevent misapplication of reductive-based technologies at sites where complete reductive dechlorination cannot be achieved. It is inappropriate to select and design an in situ enhanced reductive dechlorination technology based solely on the hydraulics of electron donor delivery and mixing. The costs for aquifer testing, modeling, system design, and installation can be a significant portion of the remedial cost. A determination that reductive dechlorination could not be stimulated as required after the system has been installed would be unfortunate, especially when the application of the RABITT protocol would have provided this information prior to moving ahead with the technology at that site.

The main weakness of the RABITT protocol is the lack of scale-up data collected during testing. Although the draft protocol was originally written to provide only a yes/no decision to proceed with the application of enhanced reductive dechlorination, the tests also provide some useful information on lag times and degradation kinetics. The tests do not provide any of the aquifer characteristics data required to design a full-scale system. Obtaining such data is technology- and site-specific and requires experienced groundwater professionals to design and implement the tests in order to ensure that high-quality data is collected as needed to accurately model and design an effective remedial system.

3. Demonstration Design

The following sections describe the performance objectives of the demonstration, the selection and characteristics of test sites, physical setup and operation, and monitoring procedures.

3.1 Performance Objectives

This project consisted of three specific objectives. First, develop a draft technical protocol that describes in detail how to conduct a treatability test for enhanced anaerobic dechlorination. Second, apply the draft protocol at four sites contaminated with chlorinated ethenes. Third, finalize the draft protocol based on the site-specific test results.

The objective of each of the four individual demonstrations was to use the draft RABITT treatability test protocol (Battelle, 1997) to evaluate whether appropriate microbial populations and geochemical conditions existed or could be produced in situ to support the biological reduction of chloroethenes to ethene. To the extent possible, treatability testing was performed in accordance with the procedures outlined in the draft RABITT treatability test protocol. The four sites selected for field demonstrations were Cape Canaveral Air Station, FL; Alameda Point, CA; Fort Lewis, WA; and Marine Corps Base Camp Lejeune, NC. Field testing and microcosm studies for the four sites took place between February 1999 and January 2002. Following completion of testing, the draft protocol was finalized based on an evaluation of data from the demonstration sites (Battelle, 2002a).

3.2 Selection of Test Sites

The selection of candidate demonstration sites was influenced primarily by technical considerations, but regulatory and political factors also played a role. Candidate sites were initially evaluated based on information supplied by Base personnel in questionnaires requesting information on a variety of subjects including the contaminant profile, geochemistry, geology, logistics, and the regulatory environment. The draft protocol contained a site rating system that was used to classify sites based on these profiles. Resulting scores were ranked on a scale that ranges from the "highest potential for success" to "prohibitive." Once a site had been selected, further screening took place to select a specific field-testing location within that site. The following paragraphs describe in further detail the technical, regulatory, and political considerations involved in overall site selection.

Technical Considerations. Because it was desired to test the protocol under a variety of field conditions ranging from promising to more challenging, only a few technical requirements were imposed on candidate demonstration sites, and most of those involved cost or feasibility considerations. The imposed technical requirements as modified for the revised protocol are listed in Table 3-1.

Regulatory Considerations. The field test described in the draft protocol specifies the extraction, amendment, and subsequent injection of nutrient-amended groundwater that is contaminated with chlorinated ethenes. This approach was selected after careful consideration of

Table 3-1. Technical Requirements for Site Selection

Criteria	Requirement/Preference
Parent compound	Only sites with PCE or TCE were considered
Level of contamination	Contaminant concentration at least two orders of magnitude greater than its detection limit, but below levels indicative of DNAPL (~1% of contaminant solubility limit)
Hydraulic conductivity	Hydraulic conductivity $>10^{-4}$ cm/sec
Groundwater velocity	Between 0.2 ft/day and 1.0 ft/day preferred, as well as areas with relatively constant and predictable groundwater flow
Depth to contamination	Sites with shallow (<50 ft bgs) contaminant plumes were preferred to reduce drilling costs
Geochemistry	Groundwater pH at a site within a range suitable for microorganisms (5 to 9 preferred)
Geology	Relatively homogeneous areas with well-defined stratigraphy preferred
Co-contaminants	Sites with commingled radioactive contamination excluded; sites screened for high concentrations of heavy metals that might affect microbial activity

several alternatives because it allows mixing of added nutrients with the groundwater and prevents the simple displacement of contaminated groundwater with a clean injection solution. Although the technical arguments for conducting the demonstration in this manner may be strong, it was assumed that the regulatory community would have concerns regarding the injection of contaminated groundwater.

At the time the draft protocol was written, there was no consensus among regulators regarding the issue of reinjection. For the protocol to function as a standardized document, it had to be applicable to the entire United States, so an effort was made to conduct demonstrations in different U.S. EPA regions and under the jurisdiction of different state regulators. Conducting demonstrations in different parts of the country was designed to provide precedents for this type of approach and hopefully pave the way for future uses of the technology. The underlying goal was to apply the protocol in different regulatory jurisdictions, but not in locations where protracted regulatory negotiations would be necessary. Ultimately, regulatory concerns about reinjection in certain regions resulted in several design options, both with and without reinjection, being presented in the revised protocol.

Political Considerations. In addition to demonstrating the protocol under various regulatory jurisdictions, it was considered important to attempt to interact with each of the four branches of the military to provide a precedent within each and help foster technology transfer. Army, Air Force, Navy, and Marine Corps installations around the country were contacted as potential host sites for a demonstration. By the end of the project, the protocol had been demonstrated successfully at installations operated by each of the four military branches.

3.3 Test Site/Facility History/Characteristics

Site descriptions, criteria for selection, and the site rating system score summary for each of the four test sites are found in the Final Technical Report (Battelle, 2002b).

3.4 Physical Setup and Operation

The step-by-step process described in the draft RABITT protocol was followed at each of the demonstration sites. The site selection process is described in Section 3.2 of this document, and the remaining phases include test preparations, microcosm testing, and field testing. Test preparations involved selecting a specific field-testing location at a given site, writing a site-specific demonstration plan, seeking regulatory approval, and performing any additional site characterization that was necessary to fill in data gaps. During this phase, the generic field-testing system described in the draft protocol was customized to address site-specific conditions. For example, the length and alignment of the test zone were specified based on the speed and direction of groundwater flow to achieve a hydraulic retention time of approximately 30 days. Customized system designs and operational parameters for each of the four demonstrations sites can be found in the Final Technical Report (Battelle, 2002b).

The remaining phases included microcosm testing and field testing. The dates along with the duration of each of these tests are listed by site in Table 3-2. The duration of field testing was approximately six months at each of the sites, and the duration of microcosm studies ranged from approximately eight months to one year.

Table 3-2. Field and Microcosm Test Completion Dates

Site	Field Testing				Microcosm Testing	
	Baseline Sampling	Injection Start Date	Treatability End Date	Duration of Injection (Months)	Start Date	End Date
Cape Canaveral	02/11/99	02/22/99	08/11/99	5.7	10/20/98	11/12/99
Alameda Point	06/03/99	06/29/99	01/10/00	6.5	12/14/98	11/16/99
Fort Lewis	08/03/00	08/31/00	02/26/01	6.0	08/22/99	06/09/00
Camp Lejeune	05/16/01	06/25/01	01/07/02	6.5	11/19/00	07/02/01

Microcosm testing involved the collection and characterization of aquifer core material and groundwater from the specific field-testing location identified during the test preparation phase. Collected core material and groundwater were used to construct microcosms and screen electron donors for their ability to stimulate reductive dechlorination. Microcosms provided insight into the rate and extent of reductive dechlorination and the fate of added reducing equivalents for each electron donor tested. Site-specific details on microcosm test setup and procedures are provided in the Final Technical Report (Battelle, 2000b). Results of microcosm testing were used to select an electron donor for use in the field.

The field testing phase included installation of the field system, tracer testing, and treatability testing. The drilling methods used to install subsurface components varied from site to site based on site-specific conditions. After all field system components were installed, a round of groundwater samples was collected to determine baseline contaminant and geochemical conditions in the aquifer. Bromide tracer testing marked the beginning of fluid injection at each of the sites. The tracer test was used to determine an appropriate injection flowrate and to ensure injected fluids could be monitored in the subsurface. Once tracer testing established that injected fluid was moving through the testing location as predicted, electron donor injection could begin. Target in situ amendment concentrations were selected based on concentrations used in the microcosm study. Site-specific installation and testing details are provided in the Final Technical Report (Battelle, 2000b) and in the site-specific technology demonstration plans (Battelle, 1999a; Battelle, 1999b; Battelle, 2000; Battelle, 2001).

3.5 Sampling/Monitoring Procedures

A rigorous sampling schedule was performed for both microcosm and field testing activities. Note that the high sampling frequency was desirable for treatability tests in order to thoroughly test the protocol; however, during standard treatability tests, less frequent monitoring will be sufficient to obtain the desired results. In fact, demonstration test results were evaluated to make recommendations for a technically sufficient yet cost-effective sampling frequency for the revised RABITT protocol.

During microcosm testing, samples were collected initially on a weekly basis and then reduced to every two weeks and eventually every month as testing progressed. In cases where respiking occurred during testing activities, the sampling frequency was increased to more closely observe changing conditions. Microcosm samples were analyzed for acetic acid, propionic acid, isobutyric acid, butyric acid, isovaleric acid, valeric acid, hexanoic acid, lactic acid, benzoic acid, ethanol, TCE, 1,1-DCE, *trans*-DCE, *cis*-DCE, VC, ethene, total volatile organic compounds (VOCs), methane, and hydrogen.

During field testing, a baseline sampling event took place prior to the initiation of treatability testing. Thereafter, samples were collected every two weeks during electron donor injection except for one site in which samples were collected every three weeks. A summary of the laboratory analytes and field parameters is shown in Table 3-3. The first demonstration site utilized a total of 49 sampling locations, whereas the other three demonstration sites utilized 12 monitoring locations each. Based on evaluation of field-test demonstration results, a reduced suite of analyses was retained in the revised protocol, as shown in Table 3-4. In addition, the sampling frequency was reduced from two weeks to one month.

3.6 Analytical Procedures

Analytical methods for field studies and microcosm studies are outlined in Sections 4.3.2 and 5.3.2, respectively, of the draft RABITT protocol (Battelle, 1997), and are discussed in further detail in the demonstration plans for the individual sites (Battelle, 1997; Battelle, 1999a; Battelle, 1999b; Battelle, 2000; Battelle, 2001).

Table 3-3. Original Sampling Plan for Field Testing Activities

	Laboratory Analytes					
Field Data	**VOCs**	**Dissolved Gases**	**Organic Data**	**Inorganic Data**	**DOC**	**H_2**
Water level Redox potential pH Temperature Bromide Dissolved oxygen Fe(II)	PCE TCE *cis*-DCE VC	Ethene Ethane Methane	Lactic acid Acetic acid Propionic acid Benzoic acid* Butyric acid*	pH Conductivity Alkalinity Nitrate Nitrite Ammonia Chloride Sulfate Bromide	Dissolved organic carbon	Dissolved hydrogen*

* Only at selected sites

Table 3-4. Analyses Retained in the Revised Protocol

Critical Analyses	Recommended Analyses
VOCs (laboratory) - PCE, TCE, *cis*-DCE, VC Dissolved gases (laboratory) - Ethene, ethane, methane Tracer (field) - Bromide	Redox potential (field) pH (field) Sulfate (field or laboratory) Organic acids (laboratory) - Organic acid analytes will depend upon the selected electron donor

4. Performance Assessment

The following sections provide an overview of field testing results and microcosm testing results, and a comparison of field and microcosm tests from individual sites. In addition, the establishment of quantitative assessment criteria is discussed.

4.1 Performance Criteria

During the development of the draft RABITT protocol, authors and reviewers attempted to outline quantitative criteria for a successful treatability test, but uncertainty regarding the overall performance of the EBRD process prevented such criteria from being included. Protocol developers were reluctant to predict lag periods or assume the extent or rate of biodegradation. The draft RABITT protocol eventually suggested that success would be defined by site-specific goals.

Shortly after the draft RABITT protocol was completed, work began on the site-specific work plan for Facility 1381 at Cape Canaveral Air Station and the issue of quantitative criteria for success was raised again. The same uncertainties that plagued the development of the draft protocol caused the assignment of modest performance objectives. The quantitative performance objective for the six-month demonstration at Facility 1381 included a 20% reduction in the mass of TCE with a concurrent equimolar increase in *cis*-DCE, VC, ethene or ethane. The rationale behind the objective was that such a finding would show that reductive dechlorination had been stimulated within the six-month testing window.

4.2 Overview of Field Results

Results from the field demonstrations showed relatively short lag periods, rapid parent compound degradation and, with the exception of one site, substantial conversion of parent compound to ethene. Table 4-1 provides an overview of the field results. Reductive dechlorination began only 3-5 weeks after starting electron donor injection. Parent compounds were quickly degraded, with half-lives measured in hours. The half-life at one site where it could not be accurately calculated is expected to be similar to half-lives observed at the other demonstration sites. A large portion of the parent compound was converted to ethene at three of the four demonstration sites in addition to being rapidly degraded. The rate, extent, and consistency of EBRD at the sites were very encouraging.

The Fort Lewis demonstration provided an interesting contrast to the other three sites. It was the only site that was initially aerobic, but it showed the most rapid dechlorination of TCE. It also demonstrated how robust an EBRD system could be. Groundwater injected into the Fort Lewis test plot consistently contained high levels of dissolved oxygen (~6 mg/L), which was no doubt quickly scavenged in the highly reducing zone immediately around the injection wells. In addition to the high dissolved oxygen levels, the plot was subjected to extraordinarily high TCE concentrations when TCE levels in the injected groundwater spiked late in the demonstration. At their peak, levels reached 169,000 parts per billion (ppb). Despite the nearly constant influx of oxygen and the extreme TCE concentrations, the rate of TCE dechlorination remained rapid and

Table 4-1. Overview of Field Results

Observation	Cape Canaveral	Alameda Point	Fort Lewis	Camp Lejeune
Parent Compound	TCE	TCE	TCE	PCE
Onset of Dechlorination	4 weeks	4 weeks	5 weeks	3 weeks
Parent Compound Half-life	Not determined	~ 20 hours	≤ 4.7 hours	≤ 164 hours
Reaction Endpoint	Ethene	Ethene	VC	Ethene
Molar Conversion to Endpoint (Plot Average)	66%	49%	<1%	5%
Molar Conversion to Endpoint (Active Monitoring Well)	MP 3-15 99+% ethene	MW-1 99+% ethene	MW-4 <1% VC	IW-2 28% ethene

MP = monitoring probe; MW = monitoring well; IW = injection well

stable. These observations indicate that EBRD is a robust process and suggest that it may be applicable to a wide variety of sites, including source zones.

Although the Fort Lewis demonstration site exhibited the most rapid dechlorination of TCE, it did not achieve the desired ethene endpoint even though two of the three butyrate-amended Fort Lewis microcosms showed complete conversion of TCE to ethene within six months. A review of microcosm data showed that the presence of parent compounds might have inhibited the dechlorination of daughter species. In the field, TCE was being constantly injected into the most highly active area of the test plot and may have inhibited the conversion of *cis*-DCE to VC. Inhibition could be avoided in future demonstrations by using a pulsed-feeding strategy that allows the depletion of parent compounds in the presence of residual electron donor, a strategy that will be incorporated into the revised protocol.

The four RABITT field demonstrations showed that EBRD quickly and effectively degrades parent chloroethenes under a variety of site conditions. The system was not susceptible to upset by changes in parent compound concentration, nor was it adversely affected by unplanned interruptions in electron donor dosing. At three of the four sites, the parent compound was converted to the nonhazardous ethene endpoint within the six-month testing window, and there is reason to believe that the fourth site might have reached that endpoint if a pulsed injection strategy had been used. The overall performance of EBRD at the four sites exceeded expectations.

4.3 Overview of Microcosm Results

The draft RABITT protocol included both microcosm and field testing so electron donors could be screened in the laboratory before being taken to the field. This approach assumed that the selection of electron donor would significantly impact dechlorination performance. Results would show that electron donor selection typically did not affect the reaction endpoint, but that it did impact the duration of the lag period and rate of dechlorination.

Table 4-2 outlines the performance of electron donors at each of the four demonstration sites by indicating the most reduced daughter product detected after six months of incubation and

specifying the molar conversion to that product in parentheses. The table shows that the selection of the electron donor typically did not change the most reduced daughter product detected, but it did influence the rate and therefore the extent of dechlorination.

Consistent reaction endpoints were observed at the Cape Canaveral, Alameda Point, and Camp Lejeune sites. At Cape Canaveral and Alameda Point ethene was detected in at least one replicate of each electron donor tested, and at Camp Lejeune all microcosms produced at least some *cis*-DCE but no VC or ethene. These results suggest that all of the electron donors tested would eventually lead to the same endpoint at a given site and that electron donor screening may not be absolutely necessary. Inconsistent results from replicate Fort Lewis microcosms made assessing electron donor performance more challenging than at the other three sites. Each of the electron donors tested did produce *cis*-DCE within the six-month testing window, and most electron donors exhibited dechlorination to VC and ethene in at least one of the three replicate bottles. Microcosms were allowed to continue incubating beyond the six-month testing window to determine if lagging bottles would eventually reach the same endpoint as more active replicates. By the end of the incubation, some of the lagging replicates had begun dechlorinating long-standing accumulations of *cis*-DCE or VC.

Although the endpoint of the dechlorination reaction was typically not affected by the choice of electron donor, the time until the onset of dechlorination and the rate of dechlorination were. The differences in lag period and dechlorination rate between donors are reflected in the extent of dechlorination reported in Table 4-2. Donors with shorter lags and/or faster dechlorination rates achieved higher molar conversions after six months. Overall, butyrate provided the most complete dechlorination within six months and therefore was selected for use at three of the four field sites; lactate did not usually lag far behind. In addition to differences in dechlorination rate, a carefully designed and monitored microcosm test can reveal information about the fate of electron donors and how efficiently they are used in the dechlorination process.

Microcosm testing provides an opportunity to examine the performance of a variety of electron donors, thereby producing useful information regarding lag periods and dechlorination rates, but that information can be corrupted by inconsistency between replicate microcosms. The unusually inconsistent results from the Fort Lewis microcosms raised some concerns that using composited core material to construct microcosms may not always overcome the heterogeneous distribution of dechlorinating activity found at a specific site. Furthermore, it may not be possible to identify a false positive microcosm result, particularly in light of the prevailing assumption that if one replicate shows more complete dechlorination it is sufficient evidence that the pathway exists at the site. Despite these concerns, microcosm testing is a useful tool that prompted the selection of an effective electron donor at each of the field demonstration sites.

Table 4-2. Overview of Microcosm Results – Dechlorination Endpoints and Molar Conversions After 6 Months

Donor	Cape Canaveral			Alameda Point			Fort Lewis			Camp Lejeune		
	Replicate			Replicate			Replicate			Replicate		
	I	II	III	I	II	III	I	II	III	I	II	III
Yeast Extract (200 mg/L)	VC (98%)	VC (98%)	E (5%)	E (100%)	E (100%)	E (62%)	E (87%)	VC (22%)	cis (100%)	cis (33%)	cis (46%)	cis (8%)
Lactate (3mM)	E (2%)	E (1%)	E (99%)	E (41%)	E (47%)	E (26%)	cis (99%)	cis (99%)	cis (99%)	cis (75%)	cis (17%)	cis (4%)
Lactate, YE, B_{12} (3mM, 20 mg/L, 0.05 mg/L)	E (4%)	E (2%)	E (2%)	E (100%)	E (67%)	E[(a)] (100%)	cis (100%)	E (73%)	cis (99%)	cis (99%)	cis (8%)	cis (9%)
Butyrate, YE, B_{12} (3mM, 20 mg/L, 0.05 mg/L)	E (8%)	E (1%)	E (21%)	E (100%)	E[(a)] (100%)	E (100%)	E (99%)	E (100%)	cis (100%)	cis (100%)	cis (100%)	cis (100%)
Lactate/Benzoate, YE, B_{12} (1.5/1.5mM, 20 mg/L, 0.05 mg/L)	E (5%)	E (15%)	E (2%)	E (3%)	E (3%)	E[(a)] (99%)	cis (100%)	cis (99%)	VC (30%)	cis (4%)	cis (3%)	cis (4%)
Propionic Acid, YE, B_{12} (3mM, 20 mg/L, 0.05 mg/L)	E (1%)	E (3%)	E (2%)	E[(a)] (99%)	E (100%)	E (100%)	cis (99%)	cis (99%)	cis (99%)	cis (100%)	cis (100%)	cis (100%)
Acetic Acid, YE, B_{12} (3mM, 20 mg/L, 0.05 mg/L)	NA	NA	NA	NA	NA	NA	cis (99%)	cis (99%)	cis (99%)	cis (3%)	cis (4%)	cis (4%)

(a) Percentage reached prior to respiking (approx. 142 days into test)
E = ethene
cis = *cis*-DCE
NA = test condition not performed for this site

4.4 Microcosm Testing versus Field Testing

The inclusion of both microcosm and field testing in the draft RABITT protocol provided an opportunity to compare the results of the two testing methodologies for consistency and to determine which provides the most cost effective approach to assessing a site's dechlorination potential. Surprisingly, results from field demonstrations corroborated microcosm results only half the time, as outlined in Table 4-3.

Table 4-3. Comparison of Microcosm and Field Results at the Four Demonstration Sites

Demonstration Site/ Electron Donor	Parameter	Microcosm Results	Field Results
Cape Canaveral/ Lactic Acid (3 mM)	Most Reduced Daughter Product	Ethene	Ethene
	Time to Appear (days)	113 – 163[(a)]	63
	Molar Conversion (%)	1 – 99	66
Alameda Point/ Butyric Acid (3 mM), Yeast Extract (20 mg/L), Vitamin B_{12} (0.05 mg/L)	Most Reduced Daughter Product	Ethene	Ethene
	Time to Appear (days)	56[(a)]	119
	Molar Conversion (%)	100	49
Fort Lewis/ Butyric Acid (3 mM), Yeast Extract (20 mg/L), Vitamin B_{12} (0.05 mg/L)	Most Reduced Daughter Product	Ethene[(b)]	VC
	Time to Appear (days)	144 – 163[(a)] (*cis*-DCE – 4)	90
	Molar Conversion (%)	100 (*cis*-DCE – 100)	<1
Camp Lejeune/ Butyric Acid (3 mM), Yeast Extract (20 mg/L), Vitamin B_{12} (0.05 mg/L)	Most Reduced Daughter Product	*cis*-DCE	Ethene
	Time to Appear (days)	1 – 5[(a)]	141
	Molar Conversion (%)	100	5

(a) Approximate time to appear based on 1% molar conversion
(b) Ethene in two of three bottles and *cis*-DCE in one bottle

The Cape Canaveral and Alameda Point demonstrations showed a good correlation between field and microcosm results. Both achieved the desired ethene endpoint relatively quickly. It is interesting to note that ethene was detected in Alameda Point microcosms before it was detected in the field. It is generally expected that microcosms will suffer longer lag periods due to the disruption caused to the aquifer material during aquifer sampling and microcosm construction, and the results from the Cape Canaveral demonstration seem to support that expectation.

The difference between the two sites may have resulted from the differing field system designs. At Cape Canaveral, a circulation system was used so there was no continuous input of parent compound at the point of electron donor injection. This resulted in a relatively rapid progression through the daughter products to achieve ethene. In contrast, the Alameda Point system received a continuous dose of parent compound at the head of the testing zone. The continuous supply of parent compound probably caused a delay in ethene production.

Unlike the results from the Cape Canaveral and Alameda Point demonstrations, results from the Fort Lewis and Camp Lejeune demonstrations showed a relatively poor correlation between field and microcosm studies. At Fort Lewis, two of three butyrate-amended microcosms showed complete conversion of TCE to ethene, but the field demonstration showed only sparing production of VC. Although this appears to be a false positive result, it needs to be recognized that microcosms did not duplicate field conditions. As noted previously, it is suspected that the continuous influx of TCE into the Fort Lewis testing zone and the subsequent accumulation of *cis*-DCE may have caused the discrepancy between field and microcosm results. In this case, the data produced by the microcosms, namely that daughter products were not degraded in the presence of parents, suggested a cause for the lack of dechlorination in the field and allowed the development of a possible solution.

At Camp Lejeune, the microcosms failed to achieve full dechlorination whereas the field test resulted in production of ethene. This false negative may have resulted from the drilling method used to retrieve the cores used for microcosm construction. The aquifer at Camp Lejeune consisted of heaving sands and required the use of mud-rotary drilling to maintain an open borehole. As a result, core material retrieved from the borehole may have been impacted by its contact with drilling fluid.

5. Cost Assessment

5.1 Cost Reporting

The following section presents actual demonstration costs for field testing and reporting at each test site as well as estimated real-world costs for field testing and microcosm studies based on the procedures described in the final RABITT protocol.

5.1.1 Actual Demonstration Costs. Actual demonstration costs for each of the four test sites were broken down according to the methodology described in the Federal Remediation Technologies Roundtable guidance document (FRTR, 1998). The RABITT process is intended to be a screening tool to select candidate sites rather than a remediation technology, so it was not possible to estimate a unit cost per volume remediated. Total demonstration costs for each of the sites ranged from $245,500 to $346,900, and are presented in Tables 5-1 through 5-4. It should be noted that costs for microcosm testing performed by Cornell University are not included in these tables.

Variability in the costs for each site is a result of numerous factors. For example, analytical costs varied significantly among sites, because analytical services were provided by the U.S. EPA for two sites at no cost whereas analytical costs for the other two sites ranged from approximately $15,000 to $44,000. The length of regulatory negotiations also varied by site. In the case of Cape Canaveral, both federal and state regulatory agencies were resistant to system design described in the draft RABITT protocol, and extensive negotiations were required to develop a system design that would accommodate all concerns and not violate Florida's strict underground injection control (UIC) regulations. As a result, regulatory negotiations consumed nearly $10,000. Other sites in states with less stringent reinjection requirements incurred only about $2,000 in regulatory negotiations. Site-specific features were another source of variability in costs among sites as reflected by costs for planning, system installation, and drilling. Furthermore, the earlier demonstration sites required that all equipment be newly purchased, whereas the later demonstration sites could utilize equipment that had been purchased for use at previous sites.

5.1.2 Estimated Implementation Costs for Revised Protocol Procedures. The cost to implement the treatability test described in the revised protocol depends on site-specific conditions (e.g., depth of contamination) and the testing methodology selected. Nonetheless, cost estimates to perform both the microcosm testing option and the field testing option described in the revised protocol are outlined below. It was necessary to make several assumptions when estimating the costs; these assumptions are also specified below.

Microcosm Testing Option. The estimated cost to perform the microcosm testing option described in the revised protocol ranges from $77,000 to $94,000. Table 5-5 shows the cost breakdown. It is assumed that five conditions will be tested using triplicate microcosms. The conditions include a killed control, a live control, and three independent electron donors. It has lso been assumed that aquifer material and groundwater will be collected from approximately 30 ft below ground surface (bgs). No travel costs have been included.

Table 5-1. Actual Demonstration Costs at Cape Canaveral Air Station

Item	Basis		Demonstration Costs
1. Capital Cost for Technology			
Mobilization	Office delivery, electrical installation		$1,000
Planning/Preparation (Labor)	Design, work plan, procurement, regulatory negotiations		$45,900
Site Work and Startup (Labor)	Installation, baseline sampling, tracer testing, system startup		$32,200
Equipment Cost			
- Well Installation	Drilling		$6,900
- Process Equipment	Pumps, controllers, stainless steel screen, gauges, other materials		$17,400
Non-Process Equipment Cost	Pumps, meters, probes, other materials		$7,900
Demobilization (Labor)	System demobilization		$4,000
		Subtotal	$115,300
2. Operation & Maintenance Cost for Technology			
O&M (Labor)	Sampling, system maintenance, data management		$74,600
Materials and Consumables	Lactic acid, sodium bromide, sampling supplies		$7,000
Utilities/Fuel	Provided by Base		$0
Equipment Cost (rental)	Office rental, probe rental		$3,600
Performance Testing/Analysis	Provided by U.S. EPA		$0
		Subtotal	$85,200
3. Other Project Costs			
Travel	Travel, per diem		$29,700
Labor - Post-Demonstration	Data analysis, reporting		$55,600
		Subtotal	$85,300
		Total Cost	**$285,800**

Table 5-2. Actual Demonstration Costs at Alameda Point

Item	Basis		Demonstration Costs
1. Capital Cost for Technology			
Mobilization	Office mobilization		$500
Planning/Preparation (Labor)	Design, work plan, procurement, regulatory negotiations		$20,700
Site Work and Startup (Labor)	Installation, baseline sampling, tracer testing, system startup		$38,600
Equipment Cost			
- Well Installation	Drilling		$22,000
- Process Equipment	Pumps, controllers, probe, other materials		$12,900
Non-Process Equipment Cost	Meters, water level indicator, storage tank		$5,900
Demobilization (Labor)			$4,000
		Subtotal	$104,600
2. Operation & Maintenance Cost for Technology			
O&M (Labor)	Sampling, system maintenance, data management		$57,400
Materials and Consumables	Butyric acid, yeast extract, other chemicals, sampling supplies		$7,400
Utilities/Fuel	Provided by Base		$0
Equipment Cost (rental)	Office rental, equipment rental		$2,700
Performance Testing/Analysis	Provided by U.S. EPA		$0
		Subtotal	$67,500
3. Other Project Costs			
Travel	Travel, per diem		$34,500
Labor - Post-Demonstration	Data analysis, reporting		$38,900
		Subtotal	$73,400
		Total Cost	**$245,500**

Table 5-3. Actual Demonstration Costs at Fort Lewis

Item	Basis		Demonstration Costs
1. Capital Cost for Technology			
Mobilization	Fence installation		$400
Planning/Preparation (Labor)	System design, work plan, procurement, regulatory negotiations		$48,600
Site Work and Startup (Labor)	Installation, baseline sampling, tracer testing, system startup		$47,800
Equipment Cost			
- Well Installation	Drilling		$36,100
- Process Equipment	Pump heads, other materials		$2,400
Non-Process Equipment Cost	Probe, other materials		$1,400
Demobilization (Labor)			$4,000
		Subtotal	$140,700
2. Operation & Maintenance Cost for Technology			
O&M (Labor)	Sampling, system maintenance, data management		$44,500
Materials and Consumables	Chemicals, sampling supplies		$5,600
Utilities/Fuel	Provided by Base		$0
Equipment Cost (rental)	Fence rental		$700
Performance Testing/Analysis	Laboratory analytical		$14,600
		Subtotal	$65,400
3. Other Direct Costs			
Travel	Travel, per diem		$25,400
Labor - Post-Demonstration	Data analysis, reporting		$38,800
		Subtotal	$64,200
		Total Cost	$270,300

Table 5-4. Actual Demonstration Costs at Camp Lejeune

Item	Basis		Demonstration Costs
1. Capital Cost for Technology			
Mobilization	Office install & remove; fence install		$2,600
Planning/preparation (Labor)	Design, work plan, procurement, regulatory negotiations		$43,100
Site Work and startup (Labor)	Installation, baseline sampling, tracer testing, system startup		$53,200
Equipment Cost			
- Well Installation	Drilling, utility locating		$20,200
- Process Equipment	Pump, pump head, other materials		$4,600
Non-Process Equipment Cost	Storage tank, electrode, meter, other materials		$4,400
Demobilization (Labor)			$4,000
		Subtotal	$132,100
2. Operation & Maintenance Cost for Technology			
Labor - O&M (Labor)	Sampling, system maintenance, data management		$93,400
Materials and Consumables	Butyric acid, yeast extract, other chemicals, sampling supplies		$6,900
Utilities/Fuel	Provided by Base		$0
Equipment Cost (rental)	Office rental		$1,600
Performance Testing/Analysis	Laboratory analytical		$44,000
		Subtotal	$145,900
3. Other Project Costs			
Travel	Travel, per diem		$30,400
Labor - Post-demonstration	Data analysis, reporting		$38,500
		Subtotal	$68,900
		Total Cost	$346,900

Table 5-5. Estimated Cost of Microcosm Testing Option

Activity	Unit Cost	Quantity	Cost
Component 1 – Site Assessment	$5-10K	1	**$5-10K**
Component 2 – Select Testing Methodology	$1-3K	1	**$1-3K**
Component 3a – Microcosm Testing			**$61-67**
Select testing location	$2-4K	1	$2-4K
Collect aquifer core material and groundwater		1	$8-10K
Labor	$2-4K	1	$2-4K
Drilling costs			
Mobilization	$0.5K	1	$0.5K
Boreholes (2 holes drilled to 30 ft bgs)	$25/lf	60 lf	$1.5K
Waste disposal	$2K	1	$2K
Misc. (decontamination, etc.)	$1K	1	$1K
Consumables and supplies	$1K	1	$1K
Conduct testing		1	$48.3K
O&M	$550/bottle	15 bottles	$8.3K
Analytical services			
VOCs	$100/sample	200 samples	$20K
Organic acids	$100/sample	200 samples	$20K
Data analysis	$3-5K	1	$3-5K
Component 4 – Reporting	$10-14K	1	**$10-14K**
Total Cost for Microcosm Testing Option			**$77-94K**

Field Testing Option. The estimated cost to complete the field testing option described in the revised protocol ranges from $84,000 to $111,000. This estimate is based on the four well extract-inject system shown in Figure 5-1, and assumes that three 1-inch polyvinyl chloride (PVC) monitoring wells will be installed to a depth of 30 ft bgs. It is assumed that an existing well will be used to collect the required background samples, and that all wells may be left intact following the demonstration. No decommission costs have been included. Table 5-6 shows the cost breakdown. It should be noted that the total estimated field testing cost presented in Table 5-6 cannot be directly compared to the total cost for actual demonstration sites, because actual costs include much more extensive sampling and reporting as well as additional categories such as travel that are not included in the estimated costs.

The selection of an alternative system design (for example, a belowground circulation system) should not seriously impact the overall cost of the field test. The fundamental cost difference between the three proposed system designs is the number of wells installed. The amount spent on materials, equipment, and monitoring should not be significantly affected. To estimate the costs in Table 5-6, it was assumed that three wells would be installed to a depth of 30 ft bgs. If only two wells are installed, as would be the case in the other two designs, the difference in cost would be approximately $1,350 less. It is assumed that a background well will always be available at a site. Presumably this would be one of the wells that initially demonstrated the presence of chlorinated solvent problem.

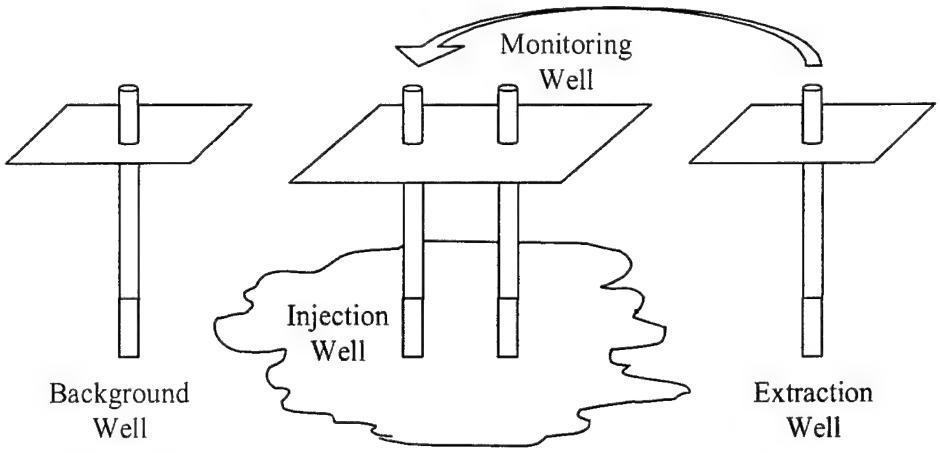

Figure 5-1. Schematic Diagram of Extract-Inject Field Testing System

Table 5-6. Estimated Cost of Field Testing Option

Activity	Unit Cost	Units	Cost
Component 1 – Site Assessment	$5-10K	1	**$5-10K**
Component 2 – Select Testing Methodology	$1-3K	1	**$1-3K**
Component 3b – Field Testing			**$68-84K**
Select testing location	$2-4K	1	$2-4K
Prepare work plan/design system	$12-17K	1	$12-17K
Install system			$18-21K
Labor	$3-5K	1	$3-5K
Drilling costs			
Mobilization	$0.5K	1	$0.5K
Three system wells (30 ft bgs)	$45/lf	90 lf	$4K
Two 1-inch PVC MWs			
One 2-inch PVC extraction well			
Waste disposal	$2K	1	$2K
Misc. (decontamination, etc.)	$1K	1	$1K
Materials	$2K	1	$2K
Equipment (pumps, tanks, etc.)	$6K	1	$6K
Conduct testing			$33-37K
Labor	$10-14K	1	$10-14K
Analytical services			
VOCs	$120/sample	32 samples	$3.8K
Organic acids	$125/sample	32 samples	$4K
Gases	$100/sample	32 samples	$3.2K
Consumables and supplies	$10K	1	$10K
Field office rental	$400/month	6 months	$2.4K
Data analysis	$3-5K	1	$3-5K
Component 4 – Reporting	$10-14K	1	**$10-14K**
Total Cost for Field Testing Option			**$84-111K**

5.1.3 Full-Scale System Costs. Due to the nature of the project and the fact that it is not intended to provide scale-up information, it was not possible to estimate full-scale system costs. However, it should be noted that the selection of electron donor will have more significant cost implications for full-scale systems than for microcosm or field RABITT demonstration tests. Therefore, electron donor selection for full-scale treatment systems should consider both cost and performance factors of candidate donors and how they will impact the overall cost and duration of treatment. The electron donor performance data gained from microcosm testing may ultimately result in cost savings for those designing large or expensive full-scale EBRD treatments systems by allowing the selection of an electron donor that minimizes the required treatment time.

5.2 Cost Analysis

5.2.1 Cost Drivers and Sensitivity Analysis. The estimated costs provided for microcosm testing and field testing in Section 5.1.2 were calculated under assumptions that were developed to describe a "typical" site. The actual costs for both types of testing will depend on site-specific requirements/logistics, so a cost comparison between the two approaches should be made during the testing methodology selection process. The variables that affect each approach and their potential impact are summarized below.

Microcosm Testing. The single variable that could most significantly impact the cost of conducting the microcosm tests is the depth of the contamination, which has a direct effect on the costs associated with collecting the aquifer core material, specifically the drilling, waste disposal and labor costs. The costs presented in Section 5.1.2 assume drilling two boreholes to a depth of 30 ft bgs. Collection of cores from shallower sites would be somewhat less expensive. For example, if the two boreholes were only 10 ft in depth the drilling costs would be decreased by a total of $1,000 assuming a unit cost of $25/ft. The cost savings associated with waste disposal would be expected to be on the order of 20% or approximately $400. Because less time is required at the shallower site, the labor costs could be expected to decrease by approximately 15%, a savings of between $300 and $600. The remaining microcosm cost variables would not be significantly impacted by the difference in contaminant depth. Adding up the cost impacts of reducing the depth by 20 ft results in a range of total costs for implementing the microcosm approach between $78,800 and $96,199.

A more dramatic effect is realized in a situation where the contamination is at 200 ft bgs. Again, the impacted cost variables would be the same but the difference in magnitude would be significant. The costs associated with drilling the two boreholes would increase to $10,000. The impact to the cost for waste disposal again is dependent on disposal requirements, the volume of soil that must be handled as waste, and the agreement with the waste hauler, and could run as high as $10,000, which is an $8,000 increase. Finally, the labor cost associated with drilling two 200-ft boreholes would increase by approximately $1,000. This results in a cost differential of +$17,500, resulting in a range of costs between $94,500 and $111,500.

Another area where cost savings may be realized is the cost for analysis. Laboratories that have automated in-house analytical capabilities should be able to provide those services for lower costs than an outside analytical laboratory. Depending on the costing practices of the lab, a savings of as much as $20,000 could be expected.

Field Testing. Similar to the microcosm approach, the most significant cost variable for the field approach is the depth to the contamination. The impact that depth has on the costs, however, is much more pronounced. Not only is the system installation cost impacted, but the cost of conducting the test is impacted as well. The potential magnitude of the impact is illustrated using the same two scenarios presented for microcosm testing. First, for a 10-ft-deep site, the drilling costs for the three system wells would decrease to $1,350 (a savings of $2,700) and waste disposal costs would decrease by approximately 20% (a savings of $400). Labor costs associated with system installation could be reduced by 15%, resulting in a labor cost range of $2,550 to $4,250, but labor costs associated with the operation and maintenance of the system would not be significantly affected. Based on these cost impacts, the cost of implementing RABITT at a 10-ft-deep site would likely range from $80,500 to $107,200.

Implementing RABITT at a 200-ft-deep site would realize a more dramatic cost impact. The cost of labor for system installation would double to between $6,000 and $10,000. The costs of the three wells and waste disposal would increase almost seven times to $26,700 and $13,500, respectively. The labor costs for conducting the test would increase approximately 30%, primarily because of the need for bailing the wells, to between $13,000 and $18,200. Adding up all of these cost impacts shows that the cost of implementing RABITT at a 200-ft-deep site likely would range between $124,200 to $154,000.

As is the case for microcosm testing, significant cost savings also can be realized depending on the selection of an analytical laboratory and the desired test methods.

5.2.2 DoD Applicability and Cost Savings. A 1997 report estimated that DoD owned more than 3,000 sites in the United States contaminated with chlorinated hydrocarbons (U.S. EPA, 1997) and new spills continually add to the problem. Almost 500 new chlorinated hydrocarbon spills at DoD sites were reported to the U.S. EPA between 1987 and 2000 (U.S. EPA, 2001). The sheer magnitude of this problem provides a compelling incentive to find cost-effective remedies.

The potential cost savings derived from use of the RABITT protocol is twofold. First, the protocol should foster the use of EBRD by alleviating concerns about it performance to base environmental managers. By encouraging the use of this relatively inexpensive approach to site remediation, the protocol holds the potential to save the DoD millions of dollars. The ultimate cost savings will depend upon the design of the full-scale treatment systems, but the very rapid degradation of parent compound observed in the four demonstrations of this project suggest that cleanup will be achieved much more efficiently than with a competing technologies such as MNA or pump and treat.

The second potential cost savings offered by the protocol is its ability to prevent the use of EBRD at sites that do not demonstrate efficient parent compound degradation. Because it is unclear how many sites will fit into this category, it is difficult to estimate a total savings, but it is presumed based on published results that a relatively small proportion of sites will have strongly superior treatment alternatives. Because EBRD is not frequently used at the current time, the cost savings may not be substantial; however, if the protocol is successful at fostering the use of EBRD, the cost savings may become significant.

5.3 Cost Comparison

The RABITT protocol is unique in that it is a screening technology rather than a remediation technology; therefore, it is inappropriate to compare its associated costs with those of conventional chlorinated solvent remediation technologies.

6. Implementation Issues

6.1 Cost Observations

The following items are key factors affecting project costs as observed from demonstration projects and, where appropriate, considerations for reducing those costs in future applications of the RABITT technology:

- Drilling costs can have a large impact on overall project costs, as demonstrated in the cost sensitivity analysis in Section 5.2.1. The primary reasons for elevated drilling costs are large depth to contamination or complicated site logistics. Drilling costs are reduced significantly at shallow sites and can be further reduced by utilizing existing site wells when possible.

- Capital costs can be reduced significantly if the RABITT treatability test is applied at multiple sites, because pumps, metering devices, and monitoring equipment can be reused at successive sites.

- Shipping and freight charges contributed a significant amount to the cost of chemicals (often as much as 40%). This should be considered in cost estimations and selection of electron donors and vendors. Significant cost savings could be experienced if local suppliers are available.

- Laboratory analytical costs contributed a significant amount to the overall cost of the demonstration projects (except in cases where the U.S. EPA provided analyses at no cost). Recommendations for extensive monitoring were incorporated into the draft protocol to ensure that sufficient data was collected for a thorough evaluation of the protocol. This level of monitoring will not be required in future RABITT treatability tests performed according to the revised protocol. These cost savings are reflected in the cost estimates provided in Tables 5-5 and 5-6.

- Costs for regulatory negotiations can vary widely depending on the regulatory climate, the openness of regulators to innovative technologies, and the existence of regulations prohibiting the injection of contaminated groundwater. The cost associated with regulatory negotiations was as much as five times higher at one demonstration site than it was for the others. Location and regulatory climate should be considered before implementing a RABITT treatability test.

- Estimated costs associated with field testing for a "typical" site were slightly higher than those associated with microcosm testing; however, both fell within a similar range. However, there is the potential for greater variability in costs of a field demonstration depending on site-specific conditions (i.e., greater depth to contamination).

- Although the field and microcosm testing methodologies have complementary strengths and weaknesses, the information they provide was determined to be too redundant to justify the cost of performing both. Selection of the testing methodology will depend upon site-specific conditions (e.g., small plume) and biases (e.g., desire to achieve some cleanup during testing).
- Utility costs for this technology are relatively low. At the Camp Lejeune demonstration site the total power consumption was only 1,009 kilowatt-hours; nonetheless, each of the four demonstrations did benefit from a cost savings because the respective bases provided electrical service. A slight increase in costs would be incurred at sites where this provision is not made.

6.2 Performance Observations

The following items summarize performance observations made during field and microcosm testing and the impacts of these observations on the future implementation of the RABITT protocol:

- Results from the field demonstrations showed relatively short lag periods, rapid parent compound degradation and, with the exception of one site, substantial conversion of parent compound to ethene. Reductive dechlorination began only 3-5 weeks after starting electron donor injection, and parent compounds were degraded quickly, with half-lives measured in hours.

- Microcosm testing showed that selection of the electron donor typically did not change the most reduced daughter product detected, but it did influence the rate and therefore the extent of dechlorination. Although the endpoint of the dechlorination reaction typically was not affected by the choice of electron donor, the time until the onset of dechlorination and the rate of dechlorination were. Donors with shorter lags and/or faster dechlorination rates achieved higher molar conversions after six months. Overall, butyrate provided the most complete dechlorination within six months and therefore was selected for use at three of the four field sites; lactate usually did not lag far behind.

- The comparison of microcosm and field data from the four RABITT demonstration sites revealed that each testing methodology had strengths and weakness, but that neither was clearly superior in every case.

- The strength of microcosm testing is its ability to screen the performance of a variety of electron donors under controlled conditions. Results from the RABITT demonstration sites clearly show that the selection of the electron donor can significantly alter the rate of dechlorination, which in turn could dramatically impact the duration of a cleanup operation. The weakness of microcosm testing stems primarily from the fact that they may not always accurately reflect the existing

subsurface conditions. A well-developed sampling plan and careful sampling and microcosm construction techniques can help overcome these obstacles.

- The strength of field testing lies in its fidelity to in situ conditions and the fact that it impacts a much larger mass of subsurface material, thereby reducing potential problems caused by the heterogeneous distribution of dechlorinating activity. The weaknesses of field testing include its susceptibility to heterogeneous or unpredictable hydrogeology, and the difficulty involved with testing multiple electron donors.

6.3 Scale-Up

The treatability tests described in the protocol were not intended to be pilot tests that would yield scale-up data for application of the reductive dechlorination process in full-scale implementation. Such testing would require extensive aquifer characterization and modeling for effective electron donor delivery and in situ mixing, which is technology-specific and beyond the scope of the RABITT protocol. Instead, the protocol was developed to determine if reductive dechlorination can be achieved by simply engineering a system to add electron donor, or if an alternative technical approach is required.

The RABITT treatability test provides a qualitative answer to whether indigenous microorganisms can be stimulated to reductively dechlorinate chloroethenes at a specific site. Although dechlorination kinetics may be available from the test, they cannot be exclusively used to design a full-scale RABITT system. Full-scale design will require a detailed understanding of subsurface hydrogeology throughout the entire contaminated zone.

6.4 Lessons Learned

The following list summarizes some of the lessons learned from conducting microcosm and field tests for the four demonstration sites:

- Results from the demonstration sites do not justify the time and expense required to perform both microcosm testing and field testing.

- The consistently strong performance of electron donors such as butyrate, lactate, and yeast extract and the generally similar dechlorination endpoints of all donors suggest that electron donor screening at every site may not be necessary.

- When performing microcosm studies, it is recommended that a limited number of conditions, including the most promising electron donors, be used. There is no compelling reason to retain the various nutrient amendments (e.g., Vitamin B_{12}) described in the draft RABITT protocol as variable test conditions.

- Respiking microcosms with parent compound after it has been depleted may cause an increase in the time to daughter product degradation and therefore is not recommended.

- Results from the four demonstration sites showed that complete depletion of electron acceptor depletion is not necessary to achieve complete dechlorination to ethene. For example, complete reductive dechlorination to ethene was observed at Alameda Point in the presence of sulfate.

- When an extract-inject treatability test system is installed, the concentration of parent compound in the supply well is considerably more important than the concentration in the testing zone, as the water in the testing zone will presumably be displaced by injected groundwater. The concentration of contaminant in the testing zone is relevant primarily because regulators may be hesitant to allow the injection of highly contaminated groundwater into an area with little or no contamination. In addition, the dechlorination process may occur more rapidly in an area that has been previously exposed to chloroethenes.

- Although the simplicity of a single standardized field-testing design is appealing, it may be impossible to design a system that adequately addresses the diverse technical and regulatory issues that can be encountered. For this reason, the revised RABITT protocol describes three alternative designs.

- Individual monitoring wells located 10 ft or less from the point of electron donor injection were consistently within the active treatment zone and independently demonstrated the sequential reduction of chloroethenes. This suggests that a single monitoring well located near the injection well (<10 ft) is sufficient to examine the dechlorination activity resulting from electron donor injection.

- The in situ treatment mechanics observed at the four demonstration sites show that an effective full-scale treatment system would not require the distribution of electron donor throughout a dissolved plume.

- EBRD is a robust process that is not adversely affected by interruptions in electron donor injection or high concentrations of parent compound. Because EBRD follows pseudo-first order kinetics and can tolerate relatively high concentrations of parent compound, its use in source zones appears to be a promising strategy for site remediation.

6.5 End-User Issues

The simplified nature of the field treatability test described in the revised protocol requires relatively little expertise in the area of bioremediation to analyze the test results. Protocol users are directed to determine the endpoint of the dechlorination process; presumably, the production of ethene will be the desired endpoint for most users. The relative proportion of parent compound to ethene should be calculated on a molar basis. A 10% conversion of parent compound to ethene suggests that the process works well at that particular site.

Another factor discussed in the revised protocol that may determine the suitability of EBRD at a site is the production of methane gas. The onset of methanogenesis indicates that subsurface conditions have become highly reduced and that electron acceptors in the testing zone are nearing exhaustion; however, the production of methane requires the consumption of electron donor that could otherwise be used in the dechlorination process. At sites where relatively high levels of electron donor are added, the potential exists for methane to accumulate at potentially hazardous levels. It may be possible to balance methane production and dechlorination activity by adjusting the dose of electron donor.

6.6 Approach to Regulatory Compliance and Acceptance

The main regulatory issue associated with the implementation of a RABITT treatability test is the injection of contaminated groundwater. Regulations have been created to protect aquifers from the introduction of hazardous substances. Although the benefits of these regulations are numerous, at times they do have the unintended consequence of complicating the use of in situ remedial systems that require the extraction and subsequent injection of contaminated groundwater. As a result, individuals or organizations considering the use of in situ remedial technologies must sometimes navigate a complex web of federal, state, and local regulations prior to receiving regulatory approval for this type a system.

Despite these regulatory obstacles, approval was granted to allow injection of contaminated groundwater amended with the electron donor and nutrients at three of the four RABITT demonstration sites. Approval typically was granted on the grounds that the addition of the electron donor and nutrients amounted to "substantial treatment" of the groundwater, as required in the regulations.

In December 1998, the Interstate Technologies Regulatory Council (ITRC) published a document entitled "Technical and Regulatory Requirements for Enhanced In Situ Bioremediation of Chlorinated Solvents in Groundwater." The document, which can be accessed at http://www.itrcweb.org, provides a useful discussion of regulatory issues associated with in situ bioremediation and outlines regulations in 24 states on a state-by-state basis.

7. References

Battelle. 1997. *Draft Technical Protocol: A Treatability Test for Evaluating the Potential Applicability of the Reductive Anaerobic Biological In Situ Treatment Technology (RABITT) to Remediate Chloroethenes.* December.

Battelle. 1999a. *Final Technology Demonstration Plan for Reductive Anaerobic Biological In Situ Treatment Technology (RABITT) Treatability Testing at Facility 1381, Cape Canaveral Air Station, FL.* March.

Battelle. 1999b. *Final Technology Demonstration Plan for Reductive Anaerobic Biological In Situ Treatment Technology (RABITT) Treatability Testing at Site 4, Alameda Point, CA.* May.

Battelle. 2000. *Final Technology Demonstration Plan for Reductive Anaerobic Biological In Situ Treatment Technology (RABITT) Treatability Testing at the East Gate Disposal Yard Site, Fort Lewis, WA.* May.

Battelle. 2001. *Final Technology Demonstration Plan for Reductive Anaerobic Biological In Situ Treatment Technology (RABITT) Treatability Testing at Site 88, Camp Lejuene, NC.* April.

Battelle. 2002a. *Final Technical Protocol: A Treatability Test for Evaluating the Potential Applicability of the Reductive Anaerobic Biological In Situ Treatment Technology (RABITT) to Remediate Chloroethenes.* November.

Battelle. 2002b. *Final Technical Report for Reductive Anaerobic Biological In Situ Treatment Technology (RABITT) Treatability Testing.* October.

Defense Environmental Restoration Program (DERP). 2001. Installation Remediation Program (IRP) Goals for active installations and FUDS properties. www.dtic.mil/envirodod/DERP/DERP.htm www.dtic.mil/envirodod/CProgram/InstRestor/CPInstalR.htm Fiscal Year 2001 Defense Environmental Restoration Program Annual Report to Congress

DiStefano, T.D., J.M. Gossett, and S.H. Zinder. 1991. "Reductive Dechlorination of High Concentrations of Tetrachloroethene to Ethene by an Anaerobic Enrichment Culture in the Absence of Methanogenesis." *Applied and Environmental Microbiology 57*(8):2287-2292.

Federal Remediation Technologies Roundtable. 1998. *Guide to Documenting and Managing Cost and Performance Information for Remediation Projects (Revised Version).* EPA 542-B-98-007. October 1998. www.frtr.gov

Major, D.W., E. Hodgins, and B. Butler. 1991. "Field and Laboratory Evidence of In Situ Biotransformation of Tetrachloroethylene to Ethene and Ethane at a Chemical Transfer Facility in North Toronto." In R. Hinchee and R. Olfenbuttel (Eds.), *On-Site Bioreclamation Processes for Xenobiotic and Hydrocarbon Treatment*. Pp. 147-171. Butterworth-Heinemann, Boston, MA.

United States Environmental Protection Agency, 1997. *Cleanup of the nation's waste sites: Markets and technology trends*. EPA 542-R-96-005. April.

United States Environmental Protection Agency. 2001. Envirofacts Warehouse: Toxic Releases; Toxics Release Inventory URL: http://www.epa.gov/enviro/html/toxic_releases.html (Page last updated on 8/13/01)

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